AMMRC TR 77-13

AD

ADA040931

YIELD STRENGTH PHENOMENON IN Ti-6Al-4V

PAUL J. FOPIANO and STEPHEN A. OLIVER
METALS RESEARCH DIVISION

April 1977

Approved for public release; distribution unlimited.

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. ~~REPORT NUMBER~~ (14) AMMRC-TR-77-13
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) YIELD STRENGTH PHENOMENON IN Ti-6Al-4V
5. ~~TYPE OF REPORT & PE~~RIOD COVERED (9) Final Report
6. PERFORMING ORG. ~~REPO~~RT NUMBER
7. AUTHOR(s) (10) Paul J. Fopiano ~~and~~ Stephen A. Oliver
8. CONTRACT OR GRANT NUMBER(s) (16)
9. PERFORMING ORGANIZATION NAME AND ADDRESS
   Army Materials and Mechanics Research Center
   Watertown, Massachusetts 02172
   DRXMR-EM
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK ~~UNIT NUMBERS~~
    D/A Project: 1L162105AH84
    AMCMS Code: 612105.H840011
    Agency Accession: DA OD4755
11. CONTROLLING OFFICE NAME AND ADDRESS
    U. S. Army Materiel Development and Readiness Command, Alexandria, Virginia 22333
12. ~~REPORT DATE~~ (11) April 1977
13. ~~NUMBER OF PAGES~~ 7
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 10p.
15. SECURITY CLASS. (of this report) Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

    Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

    Titanium alloys
    Mechanical properties
    Deformation
    Phase transformations

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

    (SEE REVERSE SIDE)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

403 105

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

1B

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Block No. 20

ABSTRACT

The titanium alloy Ti-6Al-4V has a very low yield strength (LYS) when water quenched from 850 C. This LYS is often attributed to the deformation-induced transformation of retained beta to martensite. This report gives evidence that it is not accurate to postulate a TRIP (transformation-induced plasticity) type of mechanism to explain the LYS in the 6-4 alloy.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

INTRODUCTION

The low yield strength (LYS) of specimens of Ti-6Al-4V (6-4) water quenched from 850 C has long been known[1] (see Figure 1). The correlation of this LYS with high tensile ductility and increased fracture toughness was also demonstrated. In general, this LYS has been attributed to the deformation-induced transformation (DIT) of the retained beta to martensite. The purpose of this paper is to present evidence which suggests that it is not necessary or probably accurate to postulate a TRIP (transformation-induced plasticity) type of mechanism in order to explain the LYS or even the entire yield strength versus solution temperature curve shown in Figure 1; nor is it necessary to invoke the presence of orthorhombic martensite (α'') to explain the yield strength response. As will be shown later, the presence of α'' would not be expected to have any great influence on the strength of the 6-4 alloy in either the ST (solution treated) or STA (solution treated and aged) conditions for normal temperatures of heat treatment.

RETAINED BETA

In a recent report,[2] the equilibrium composition of the beta phase for specimens of 6-4 solution treated at 850 C was determined to be approximately 8 weight percent (w/o) vanadium and 4.5 w/o aluminum. This then is the composition of the beta phase which exhibits the marked LYS in 6-4. A small arc-melted button of

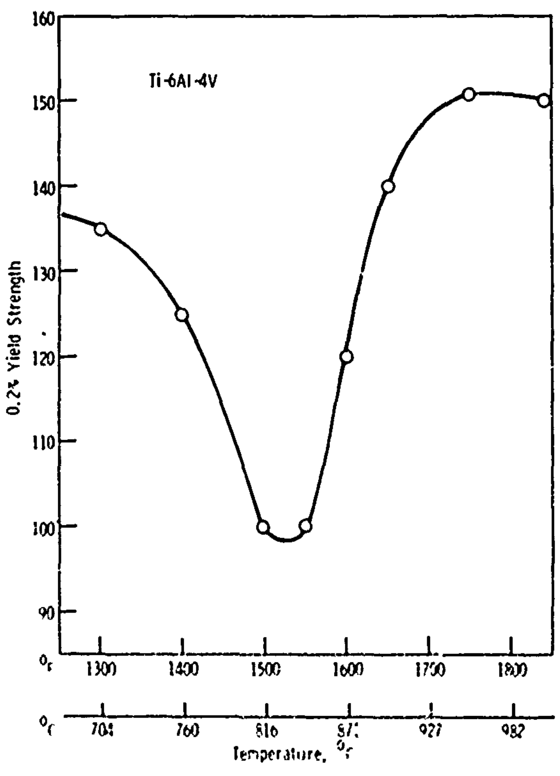


Figure 1. Yield stress versus solution temperature in the Ti-6Al-4V alloy.

1. SHERMAN, R. G., and KESSLER, H. D. *Investigation of the Heat Treatability of the 6% Aluminum 4% Vanadium Titanium-Base Alloy.* Trans. ASM, v. 48, 1956, p. 657.
2. FOPIANO, P. J., and COMERFORD, M. F. *An Investigation of the Equilibrium Alpha and Beta Phases in the Alloy Ti-6Al-4V.* Army Materials and Mechanics Research Center, AMMRC TR 73-44, October 1973.

this alloy was forged and homogenized. Only hexagonal-close-packed (hcp) alpha was observed by X-ray diffraction and light microscopy (Figure 2) indicating that this was hcp martensite (α'). No evidence of retained beta was found which, for the X-ray technique employed, indicated the presence of less than 3 volume percent retained beta.

Comerford et al.,[3] on the same heat of material as in Reference 2, also found no evidence for retained beta in 6-4 specimens quenched from 850 C. These investigators employed a diffracted beam monochromator and estimated the limit of resolution to be at least 0.5 volume percent. We are not aware of any X-ray diffraction work indicating the presence of retained beta in specimens of 6-4 solution treated and quenched from 850 C.

More recently, Modin and Modin,[4] using a JEOL 1 MeV electron microscope, found no evidence of retained beta in specimens of 6-4 which had been isothermally transformed at 850 C and quenched to room temperature. These same investigators[5] found no evidence of retained beta in specimens isothermally transformed at 750 C and conclude that all of the beta transformed to alpha leaving no beta nuclei.

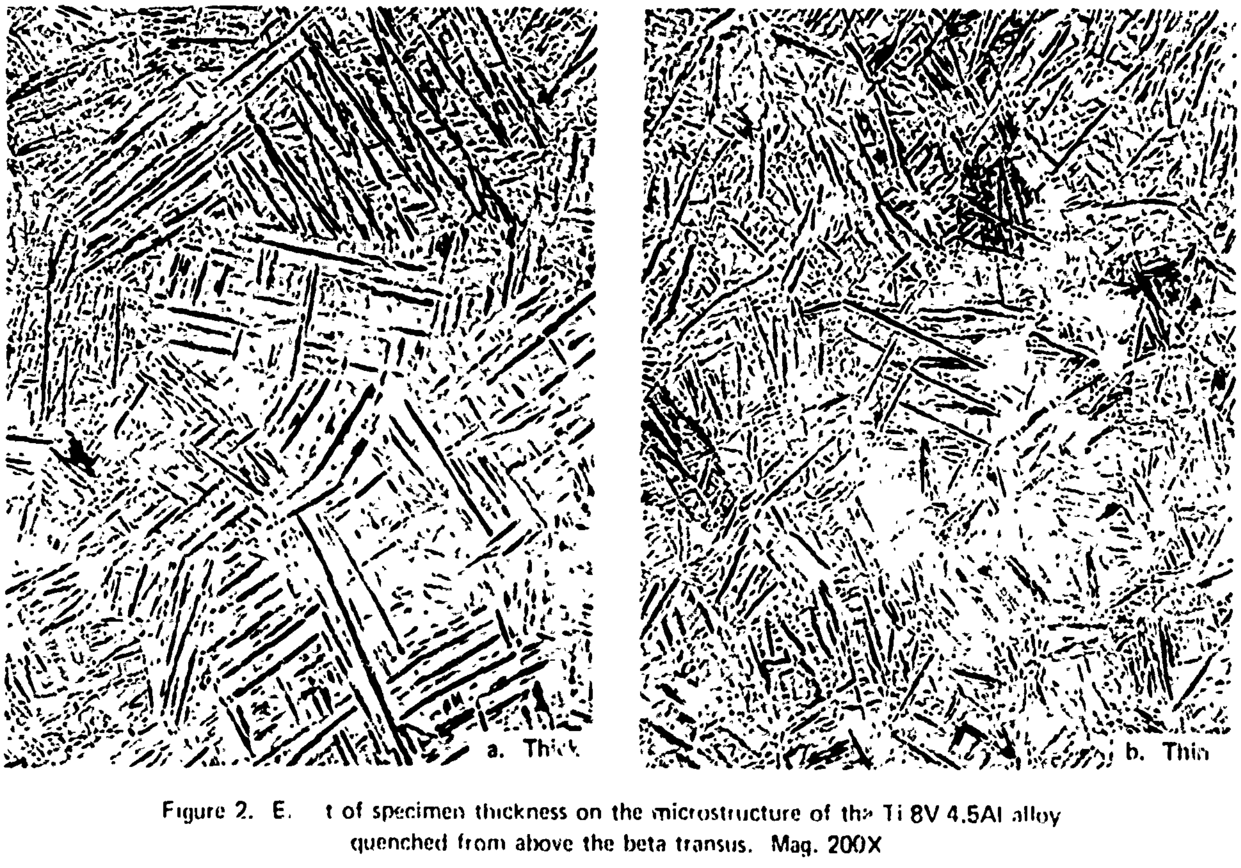


Figure 2. E t of specimen thickness on the microstructure of the Ti 8V 4.5Al alloy quenched from above the beta transus. Mag. 200X

3 AVERBACH, B. L., COMERFORD, M. F., and BEVER, M. B. *An X-Ray Method for the Determination of Beta Phase in a Titanium Alloy.* Trans. Met. Soc., AIME, v. 215, 1959, p. 682.

4 MODIN, H. and MODIN, S. *Phase Transformations in the Titanium Alloy Ti-6Al-4V.* Jernkont. Ann., v. 155, 1971, p. 425.

5 MODIN, H., and MODIN, S. *Metallografisk Undersokning av Titanlegeringen Ti-6Al-4V.* Report 920 from the Swedish Institute for Metals Research, January 1973.

Presumably the nucleation of beta was slow at this temperature. At equilibrium, of course, the beta phase is observed in specimens of 6-4 solution treated at 750 C.[3]

In summary, therefore, there seems to be no direct evidence for the presence of retained beta in 6-4 specimens quenched from 850 C. The martensite that does form is hexagonal close packed.

EFFECT OF COOLING RATE

A thick (approximately 1/4") and a thin (0.030 to 0.040") specimen of the alloy 8V-4.5Al (8-4.5) were solution treated above the beta transus and ice brine quenched (Figure 2). The hardness of the thin specimen was found to be 4 R_c units lower than the thick specimen. Since there is no reason to believe that a faster quenching rate should affect the amount of retained beta (in fact, no retained beta was observed in either specimen by X-ray diffraction), the higher hardness in the thick specimen must be due to the very rapid decomposition of the martensitic α' during the somewhat slower quenching rate in the thicker specimen.

Similar effects are observed in the 6-4 alloy. Bulk disk test specimens and fine powders were both solution treated at 920 C and rapidly cooled. The as-quenched hardness values of the powder were much lower than for the bulk specimens. In both cases a very short aging time (less than 5 minutes at 538 C) increased the hardness of both samples to approximately the same hardness value. The rapid destruction of LYS by aging, therefore, cannot be due to the much slower diffusion controlled decomposition or alloy enrichment of the retained beta.

ORTHORHOMBIC (α'') MARTENSITE

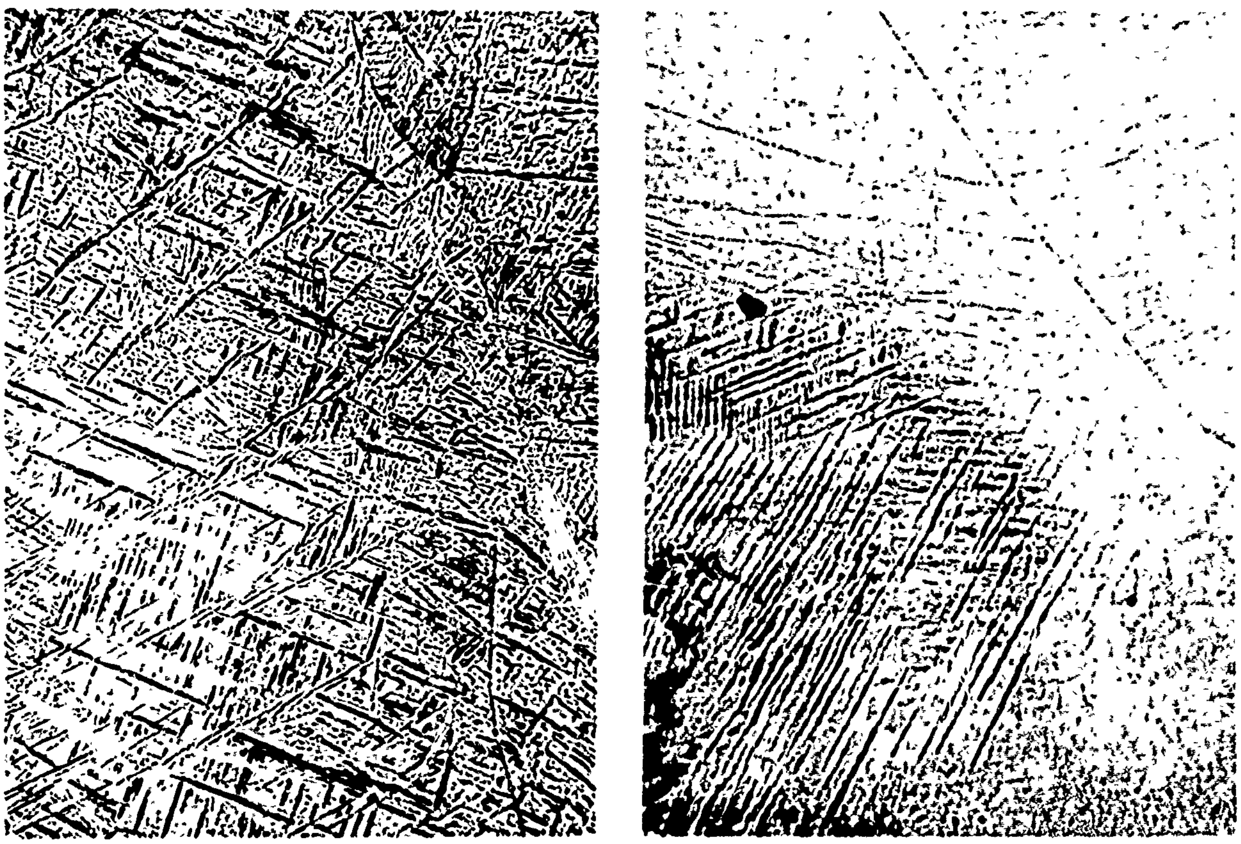
Along with the DIT mechanism for the LYS, it is often inferred that the presence of α'' is somehow necessary to explain the strengthening response of 6-4 as a function of solution temperature (Figure 1). It is our contention that α'' contributes little to the strengthening of 6-4 in the ST and STA conditions for normal heat treatment sequences.

Based on extensive observations by Williams and co-workers,[6] Middleton and Hickey[7] for transage 129, and the present authors on Ti-Nb alloys, α'' is formed both athermally for certain alloy compositions and by mechanical deformation for other compositions sufficient to just stabilize the beta phase. It would be α'' which would presumably form by DIT in the 6-4 alloy quenched from 850 C. That α'' is not actually observed by X-ray diffraction is readily rationalized because so little α'' forms and is masked by cold work broadening effects.

We have observed that a 15V-2Al (15-2) titanium alloy transforms predominantly to α'' when quenched from the beta region. The 15-2 alloy is the composition of the beta phase in a 6-4 alloy which has been quenched from between 700

6. WILLIAMS, J. C. *Critical Review Kinetics and Phase Transformations.* Titanium Science and Technology, ed. by R. I. Jaffee and H. J. Burte, Plenum Press, New York, 1973, p. 1433.
7. MIDDLETON, R. M., and HICKEY, C. F., Jr. *Transformation Characteristics of Ti Transage 129.* Presented at the Spring Meeting AIME, IMD in Pittsburgh, Pennsylvania, May 20-23, 1974.

to 750 C. These temperatures are well below the LYS range in the 6-4 alloy. Upon reheating, it was observed by resistance measurements that the α" in the 15-2 alloy began to revert to the beta phase at about 265 C. The reversion of α" is accompanied by a drop in resistance which has been well documented in the Ti-Nb system by the present authors.* The reversion of the α" in the 15-2 alloy is confirmed not only by X-ray diffraction but also very graphically by the two light micrographs in Figure 3. The predominant phase in the reverted structure (Figure 3b) is beta with only patches of martensite in some of the grains. Since 6-4 specimens in the ST 700 to 750 C condition indicated no measurable change in strength upon subsequent aging,[8] the predominant presence of orthorhombic martensite in the ST condition and its reversion to beta in the STA condition is seen to have very little effect on the mechanical properties. The omega phase does not form in this alloy for the heat treat conditions under consideration here. The presence, if any, of trace amounts of α" in specimens of 6-4 solution treated at 850 C and higher is therefore not expected to materially affect the mechanical properties. In fact, however, there is no evidence for the presence of α" in specimens of 6-4 solution treated at and above 850 C.



a. As-Quenched

b. Quenched and Reverted

Figure 3. Microstructures of the Ti-15V-2Al alloy quenched from above the beta transus Mag. 100X

*Investigations of Phase Transformations in Ti-Nb, in preparation

8. LOPIANO, P. J., BEVER, M. B., and AVERBACH, B. L. *Phase Transformations and Strengthening Mechanisms in the Alloy Ti-6Al-4V.* Trans. ASM, v. 62, 1969, p. 324.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
YIELD STRENGTH PHENOMENON IN Ti-6Al-4V -
Paul J. Fopiano and Stephen A. Oliver

Technical Report AMMRC TR 77-13, April 1977 -
7 pp, illus, D/A Project 1L162105AH84,
AMCMS Code 612105.H840011

AD ______________.
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Mechanical properties
Deformation

The titanium alloy Ti-6Al-4V has a very low yield strength (LYS) when water quenched from 850 C. This LYS is often attributed to the deformation-induced transformation of retained beta to martensite. This report gives evidence that it is not accurate to postulate a TRIP (transformation-induced plasticity) type of mechanism to explain the LYS in the 6-4 alloy.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
YIELD STRENGTH PHENOMENON IN Ti-6Al-4V -
Paul J. Fopiano and Stephen A. Oliver

Technical Report AMMRC TR 77-13, April 1977 -
7 pp, illus, D/A Project 1L162105AH84,
AMCMS Code 612105.H840011

AD ______________
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Mechanical properties
Deformation

The titanium alloy Ti-6Al-4V has a very low yield strength (LYS) when water quenched from 850 C. This LYS is often attributed to the deformation-induced transformation of retained beta to martensite. This report gives evidence that it is not accurate to postulate a TRIP (transformation-induced plasticity) type of mechanism to explain the LYS in the 6-4 alloy.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
YIELD STRENGTH PHENOMENON IN Ti-6Al-4V -
Paul J. Fopiano and Stephen A. Oliver

Technical Report AMMRC TR 77-13, April 1977 -
7 pp, illus, D/A Project 1L162105AH84,
AMCMS Code 612105.H840011

AD ______________.
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Mechanical properties
Deformation

The titanium alloy Ti-6Al-4V has a very low yield strength (LYS) when water quenched from 850 C. This LYS is often attributed to the deformation-induced transformation of retained beta to martensite. This report gives evidence that it is not accurate to postulate a TRIP (transformation-induced plasticity) type of mechanism to explain the LYS in the 6-4 alloy.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
YIELD STRENGTH PHENOMENON IN Ti-6Al-4V -
Paul J. Fopiano and Stephen A. Oliver

Technical Report AMMRC TR 77-13, April 1977 -
7 pp, illus, D/A Project 1L162105AH84,
AMCMS Code 612105.H840011

AD ______________.
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Titanium alloys
Mechanical properties
Deformation

The titanium alloy Ti-6Al-4V has a very low yield strength (LYS) when water quenched from 850 C. This LYS is often attributed to the deformation-induced transformation of retained beta to martensite. This report gives evidence that it is not accurate to postulate a TRIP (transformation-induced plasticity) type of mechanism to explain the LYS in the 6-4 alloy.

ALTERNATIVE EXPLANATION

In Reference 8, it was shown that the density of the 6-4 alloy quenched from 850 C was low. It is the lower than normal density of unaged α' rather than the DIT of the retained beta phase to which we attribute the LYS. The low density is attributed to the incomplete contraction of the lattice during the transformation of the less dense (bcc) beta to the more dense (hcp) α'.[8]

The rapid increase in density (and hardness) with subsequent aging is attributed by Fopiano et al.[6] to the vacancy-assisted decomposition (with an activation energy of approximately 15 kcal/mol) of the martensitic α'. The LYS also disappears rapidly with aging. By the DIT mechanism, any retained beta present in the quenched specimen must either decompose or change its composition in much less than 5 minutes at 538 C (the time to reach maximum density and hardness). This is highly unlikely by any normal diffusion process.

CONCLUSION

While it is not uncommon that small amounts of a phase can bring about large changes in mechanical properties (consider the often disastrous effects of some grain boundary precipitates on fracture toughness), this does not seem to be the case for the LYS effect in the 6-4 titanium alloy. The lack of direct evidence of measurable amounts of retained beta, the rapid disappearance of LYS with aging, the effect of quench rate on hardness, and the negligible effect of α" on mechanical properties all indicate that the DIT mechanism for the LYS is not acceptable. The alternative explanation that the LYS is due to the incomplete contraction of the lattice is more consistent with the experimental observations.

DISTRIBUTION LIST

No. of Copies	To
1	Office of the Director, Defense Research and Engineering, The Pentagon, Washington, D. C. 20301
12	Commander, Defense Documentation Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, Virginia 22314
1	Metals and Ceramics Information Center, Battelle Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201
	Chief of Research and Development, Department of the Army, Washington, D. C. 20310
2	ATTN: Physical and Engineering Sciences Division
	Commander, Army Research Office, P. O. Box 12211, Research Triangle Park, North Carolina 27709
1	ATTN: Information Processing Office
	Commander, U. S. Army Materiel Development and Readiness Command, 5001 Eisenhower Avenue, Alexandria, Virginia 22333
1	ATTN: DRCLDC, Mr. R. Zentner
1	DRCSA-S, Dr. R. B. Dillaway, Chief Scientist
	Commander, U. S. Army Electronics Command, Fort Monmouth, New Jersey 07703
1	ATTN: DRSEL-GG-DD
1	DRSEL-GG-DM
	Commander, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
1	ATTN: Technical Library
1	DRSMI-RSM, Mr. E. J. Wheelahan
	Commander, U. S. Army Armament Command, Rock Island, Illinois 61201
2	ATTN: Technical Library
1	DRSAR-SC, Dr. C. M. Hudson
1	DRSAR-PPW-PB, Mr. Francis X. Walter
	Commander, U. S. Army Natick Research and Development Command, Natick, Massachusetts 01760
1	ATTN: Technical Library
	Commander, Aberdeen Proving Ground, Maryland 21005
1	ATTN: STEAP-TL, Bldg. 305
	President, Airborne, Electronics and Special Warfare Board, Fort Bragg, North Carolina 28307
1	ATTN: Library

No. of Copies	To
	Commander, Dugway Proving Ground, Dugway, Utah 84022
1	ATTN: Technical Library, Technical Information Division
	Commander, Edgewood Arsenal, Aberdeen Proving Ground, Maryland 21010
1	ATTN: Mr. F. E. Thompson, Dir. of Eng. & Ind. Serv., Chem-Mun Br
	Commander, Frankford Arsenal, Philadelphia, Pennsylvania 19137
1	ATTN: Library, H1300, Bl. 51-2
1	SARFA-L300, Mr. J. Corrie
	Commander, Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, Maryland 20783
1	ATTN: Technical Information Office
	Commander, Picatinny Arsenal, Dover, New Jersey 07801
1	ATTN: SARPA-RT-S
1	SARPA-FR-M-D, PLASTEC, A. M. Anzalone
	Commander, Redstone Scientific Information Center, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
4	ATTN: DRSMI-RBLD, Document Section
	Commander, Watervliet Arsenal, Watervliet, New York 12189
1	ATTN: SARWV-RDT, Technical Information Services Office
	Commander, U. S. Army Foreign Science and Technology Center, 220 7th Street, N. E., Charlottesville, Virginia 22901
1	ATTN: DRXST-SD2
	Director, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia 23604
1	ATTN: Mr. J. Robinson, SAVDL-EU-SS
	Librarian, U. S. Army Aviation School Library, Fort Rucker, Alabama 36360
1	ATTN: Building 5907
	Commander, USACDC Air Defense Agency, Fort Bliss, Texas 79916
1	ATTN: Technical Library
	Commander, U. S. Army Engineer School, Fort Belvoir, Virginia 22060
1	ATTN: Library
	Naval Research Laboratory, Washington, D. C. 20375
1	ATTN: Dr. J. M. Krafft - Code 8430
2	Dr. G. R. Yoder - Code 6382
	Chief of Naval Research, Arlington, Virginia 22217
1	ATTN: Code 471

No. of Copies	To
	Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433
2	ATTN: AFML/MXE/E. Morrissey
1	AFML/LC
1	AFML/LLP/D. M. Forney, Jr.
1	AFML/MBC/Mr. Stanley Schulman
	National Aeronautics and Space Administration, Washington, D. C. 20546
1	ATTN: Mr. B. G. Achhammer
1	Mr. G. C. Deutsch - Code RR-1
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama 35812
1	ATTN: R-P&VE-M, R. J. Schwinghamer
1	S&E-ME-MM, Mr. W. A. Wilson, Building 4720
	Lockheed-Georgia Company, Marietta, Georgia 30063
1	ATTN: Advanced Composites Information Center, Dept. 72-34 – Zone 26
1	Mechanical Properties Data Center, Belfour Stulen, Inc., 13917 W. Bay Shore Drive, Traverse City, Michigan 49684
	Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172
2	ATTN: DRXMR-PL
1	DRXMR-AG
2	Authors